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Two Dimensional Viscoelastic Stress Analysis of a Prototypical JIMO Turbine Wheel

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Introduction

The designers of the Jupiter Icy Moons Orbiter (JIMO) are investigating the potential of nuclear powered-electric propulsion technology to provide deep space propulsion. In one design scenario a closed-Brayton-cycle power converter is used to convert thermal energy from a nuclear reactor to electrical power for the spacecraft utilizing an inert gas as the working fluid to run a turboalternator as described in reference 1. A key component in the turboalternator is the radial flow turbine wheel which may be fabricated from a cast superalloy. This turbine wheel is envisioned to run continuously over the life of the mission, which is anticipated to be about ten years. This scenario places unusual material requirements on the turbine wheel. Unlike the case of terrestrial turbine engines, fatigue, associated with start-up and shut-down of the engine, foreign-object damage, and corrosion issues are insignificant and thus creep issues become dominate.

The purpose of this paper is to present estimates for creep growth of a prototypical JIMO turbine wheel over a ten year life. Since an actual design and bill of materials does not exist, the results presented in this paper are based on preliminary concepts which are likely to evolve over time. For this reason, as well as computational efficiency, a simplified 2–D, in lieu of a 3–D, viscoelastic, finite element model of a prototypical turbine wheel will be utilized employing material properties for the cast superalloy MAR-M247. The creep data employed in this analysis are based on preliminary data being generated at NASA Glenn Research Center.

Material

Previous closed-Brayton-cycle space power conversion demonstration units, reference 2, built under contract to NASA by Garrett and operated by NASA, have employed a cast superalloy turbine wheel. In particular the temperatures, stresses, and times encountered in these units allowed the use of the cast superalloy IN713. The proposed JIMO mission may require additional creep capability and for this reason superalloys with improved creep strength are being considered. These state-of-the-art superalloys include next generation powder metallurgy (PM) disk alloys, such as ME3 or LSHR that were developed in NASA's High Speed Research/Ultra-Efficient Engine Technology programs, as well as advanced cast superalloys, such as IN792 or MAR-M247. In general, the PM superalloys provide superior creep strength at temperatures below 1300 °F (977 K), while the advanced cast superalloys provide superior creep strength at temperatures above 1300 °F (977 K). The choice of material for the turbine wheel will depend on the final design criteria and could employ either a PM superalloy or a cast superalloy. MAR-M247 was selected for the stress analysis presented in this paper, since it represents the alloy types with the best high-temperature creep strength. As shown in figure 1, MAR-M247 has the highest allowable stress for creep rupture in one thousand hours at 1600 °F (1144 K), and therefore has the best temperature margin of the four alloys compared.

MAR-M247 is a cast, nickel-base superalloy. The composition of the alloy and heat treatment schedule used in this study are provided in table I and II. Its creep strength is derived from a high volume fraction of the gamma prime (Ni_3Al) precipitate, a significant amount of solid solution strengthening by alloying additions such as tungsten and tantalum, and the large grain size typical of superalloy castings. The typical microstructure presented in figure 2, shows a grain size of several millimeters for the cast bars currently being employed to generate creep data on MAR-M247 for this project.

Long-term creep data is being generated by NASA Glenn on MAR-M247 to support the JIMO power conversion design. These data include constant-load creep tests in air and helium over a wide range of temperatures and applied stresses. A typical creep curve is presented in figure 3. Creep rate is the slope of the creep strain versus time curve. For design purposes, creep rates are compared at a common point in the curve, 1 percent creep strain in this study. Creep rates calculated from on-going experiments are presented in figure 4. Test data at the lower creep rate regimes have not yet reached 1 percent creep strain, thus rate data are calculated by dividing current measured creep strains by total test time. Test results presented in figure 4 for higher creep rates were calculated in the standard fashion at 1 percent creep strain. The majority of data shown here were generated in air. Initial testing in helium shows comparable results for the limited data available at this time.

For the creep analysis employed in this paper the raw creep rate data plotted in figure 4 were fit with a power law creep expression:

$$\Delta\varepsilon/\Delta t = A\sigma^n$$

In the above expression, $\Delta\varepsilon/\Delta t$ is the creep rate, σ is the applied stress, while A and n are data derived constants. Using an exponent of $n = 6.7$ a good fit of the data is obtained at 1300 and 1500°F (977 and 1089 K). Values of A determined from the current data are presented in table III along with temperature-dependent values for modulus and thermal expansion rates for MAR-M247 obtained from reference 3. These values were used in the subsequent finite element analyses.

Turbine Wheel Analysis

The two-dimensional, axisymmetric turbine wheel model utilized in this paper is presented in figure 5. The blading on a 2–D model can, by definition, only approximately simulate the actual 3–D blading on a real turbine wheel. The essential characteristics of the blade simulator in this model are twofold. First, it is relatively thin, and second, it delineates the boundary between the turbine inlet and outlet gas paths. The turbine wheel model depicted in figure 5 has a 3 in. (7.62 cm) radius and was meshed utilizing the automatic 2–D mesh generator provided by the Algor™ finite element software package used in this analysis.

To begin the analysis, the steady-state heat transfer module was utilized to predict the stabilized operating-temperature distribution of the turbine wheel. To obtain the temperature map presented in figure 6 the following assumptions were made. First, the following thermophysical properties for density, thermal conductivity and specific heat of the MAR-M247 were employed:

$$\rho = 0.3\text{lbs/in}^3\ (8.3\ \text{g/cm}^3)$$
$$k = 1.0\text{Btu/hr/in/F}\ (747\ \text{J/hr/cm/K})$$
$$C = 0.1\text{Btu/lbs/F}\ (0.418\ \text{J/g/K})$$

Second, the inlet and outlet gas temperatures were assumed to be 1600 and 1200 °F (1144 and 922 K) respectively, with a heat transfer coefficient of 0.1Btu/hr/F/in^2 (29 J/hr/cm^2/K) at the gas-wheel interface. Finally, the shaft of the turbine wheel was assumed to "see" the 400 °F (477 K) compressor temperature and a heat transfer coefficient of 0.2 Btu/hr/F/in^2 (58 J/hr/cm^2/K) was employed at this surface. The temperature distribution shown in figure 6 is typical of turbine wheels of this size class. It should be noted that the maximum operating temperature is about 1400 °F (1036 K) using the aforementioned assumptions.

The turbine wheel growth model requires a viscoelastic finite element analysis. This process is broken into two parts; one part analyzing the initial loading conditions and the other part analyzing the time dependent changes over the mission life. First, the wheel speed is set to 45,000 revolutions per minute (RPM) and the wheel temperature is increased from room temperature to the operating temperatures shown in figure 6. The resulting stresses and wheel growth are presented in figure 7. The imposition of elastic and thermal loading is a rapid process in comparison to the operating lifetime of the wheel. In this analysis, the elastic and thermal loads were imposed within 2 hours for computational convenience, which is a realistic timeframe in relation to the 10 year life of the JIMO mission. The second part required continued modeling to assess stress redistribution over a 100,000 hour mission life. Time steps of 10 hours were employed for this segment of the analysis. The resulting stress distribution and growth of the wheel are presented in figure 8. Note, the overall stress distribution shows very little change and the creep growth of the wheel (node 182) and the blade simulator (node 498) are quite small compared to the elastic and thermal components of wheel growth. The most significant change in the stress distribution is seen at the shaft radius where relaxation of peak stress levels are observed.

To further explore the stability of the design and assess changes in the rate of wheel growth associated with increasing operating temperatures, the aforementioned analysis was rerun assuming a heat transfer coefficient of 0.2Btu/hr/F/in^2 (59 J/hr/cm^2/K) at the gas-wheel interface. The increase in heat transfer results in an overall temperature increase and the maximum wheel temperature approaches 1500 °F (1089 K). Comparisons of wheel growth between the initial analysis and the hotter turbine wheel are presented in figure 9. While the creep growth shows a significant increase relative to the first analysis, it is still small relative to the elastic and thermal components of wheel growth.

Summary

A two dimensional, axisymmetric, viscoelastic analysis of a prototypical JIMO turbine wheel was performed. The turbine wheel was assumed to be fabricated from a cast superalloy and had a 3 in. (7.62 cm) radius. The analysis was performed assuming a wheel speed of 45,000 rpm and using two significantly different temperature profiles. The baseline analysis had maximum blade temperatures near 1400 °F (1036 K). In this case, the creep growth after 100,000 hours was small compared to the elastic and thermal components of wheel growth. A second case, with maximum blade temperatures near 1500 °F (1089 K), showed a significant increase in creep growth relative to the first case, however, it was still less than the elastic and thermal components of wheel growth. These results suggest a superalloy turbine wheel will meet the requirements for the JIMO mission.

References

1. L.S. Mason, "A Power Conversion Concept for the Jupiter Icy Moons Orbiter," Journal of Propulsion and Power, vol. 20, no. 5, pp. 902–910.
2. J.E. Davis, "Design and Fabrication of the Brayton Rotating Unit," NASA CR-1870, March 1972.
3. INCO, "High Temperature High Strength Nickel Base Alloys," The International Nickel Company Inc., 3rd Edition, July 1977.

TABLE I.—COMPOSITION (WEIGHT PERCENT) OF MAR-M247

Cr	Co	Mo	W	Ta	Al	Ti	Hf	C	B	Zr	Ni
8.2	9.2	0.5	9.6	3.2	5.6	0.7	1.3	0.08	0.01	0.01	BAL

TABLE II.—HEAT TREATMENT SEQUENCE FOR MAR-M247

Step	Temp °F (K)	Time (hr)	Comment
1	2165 (1458)	4	Hot Isostatic Press at 25KSI (172 MPa)
2	2225 (1491)	2	Gas Quench
3	1975 (1352)	4	Gas Quench
4	1600 (1144)	20	Air Quench

TABLE III.—MATERIAL PROPERTIES OF MAR-M247 USED IN FINITE ELEMENT ANALYSIS

Temp (°F)	Modulus (PSI)	Poisson Ratio	Expansion Coefficient (F^{-1})	A	n
0	30e8	0.3	6e-6	0	6.7
1000	26e8	0.3	7e-6	0	6.7
1300	25e8	0.3	8e-6	3.3e-39	6.7
1500	24e8	0.3	9e-6	7.6e-37	6.7

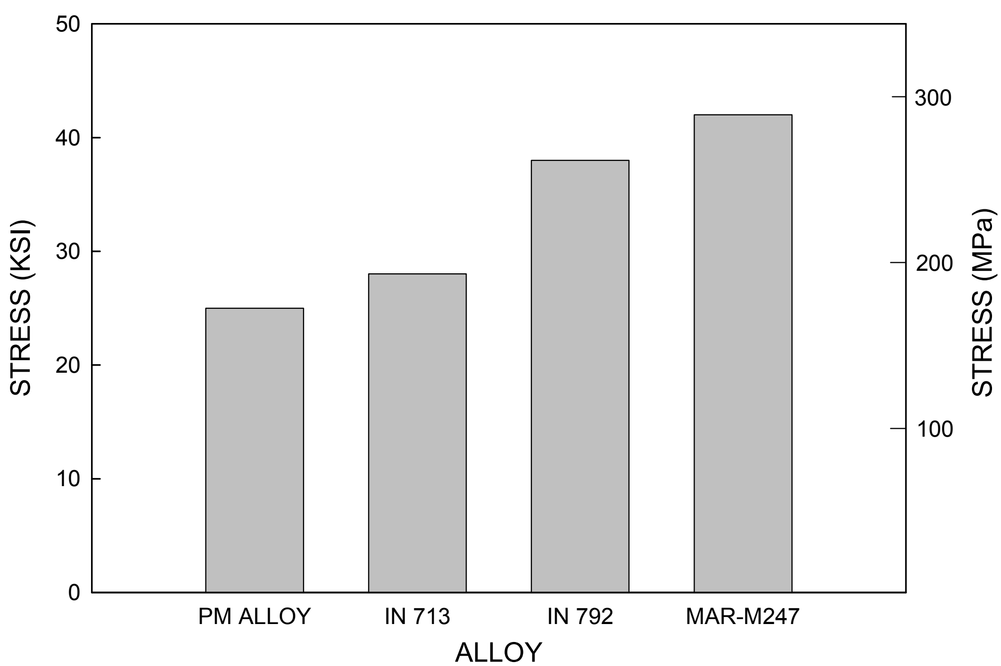


Figure 1.—Applied stress leading to thousand hour rupture life at 1600 °F (1144 K) from reference 3.

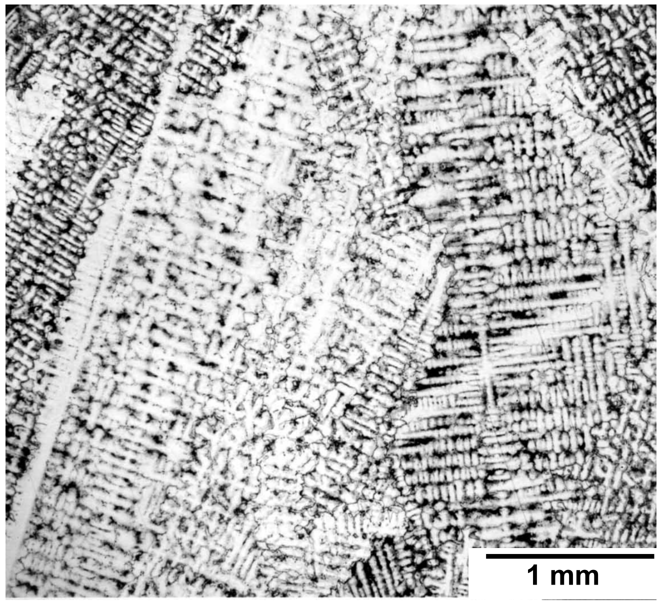


Figure 2.—Etched microstructure of MAR-M247.

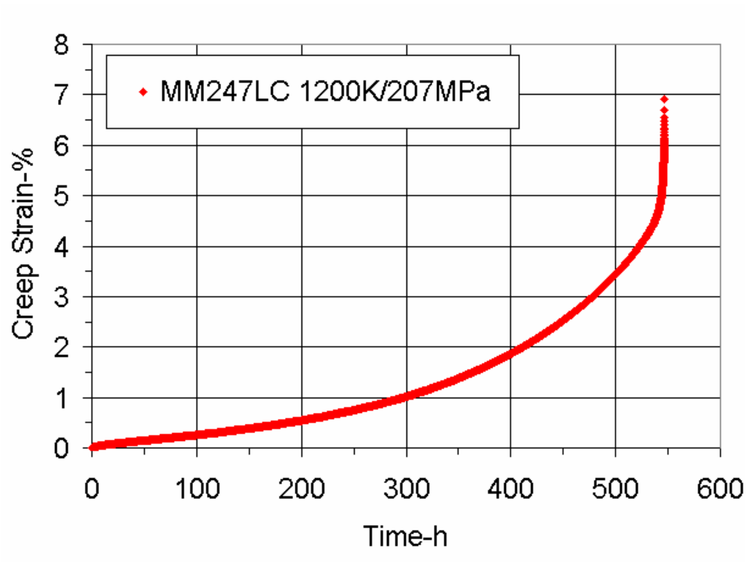


Figure 3.—Typical creep curve for MAR-M247.

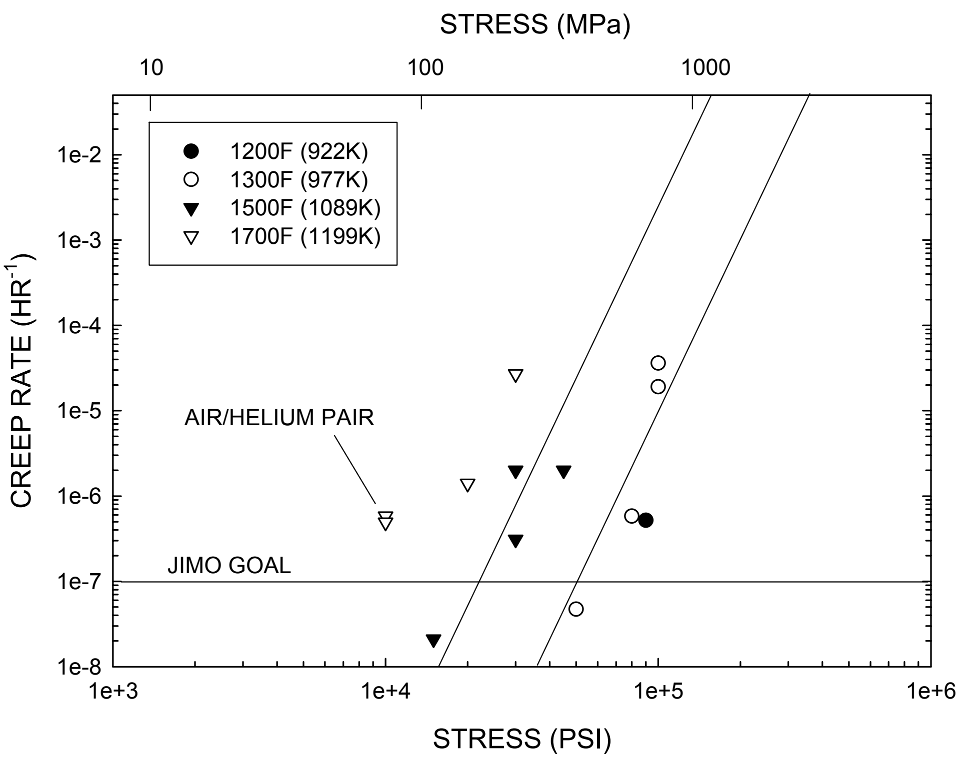


Figure 4.—MAR-M247 creep rate data from on-going experiments used in subsequent finite element analysis.

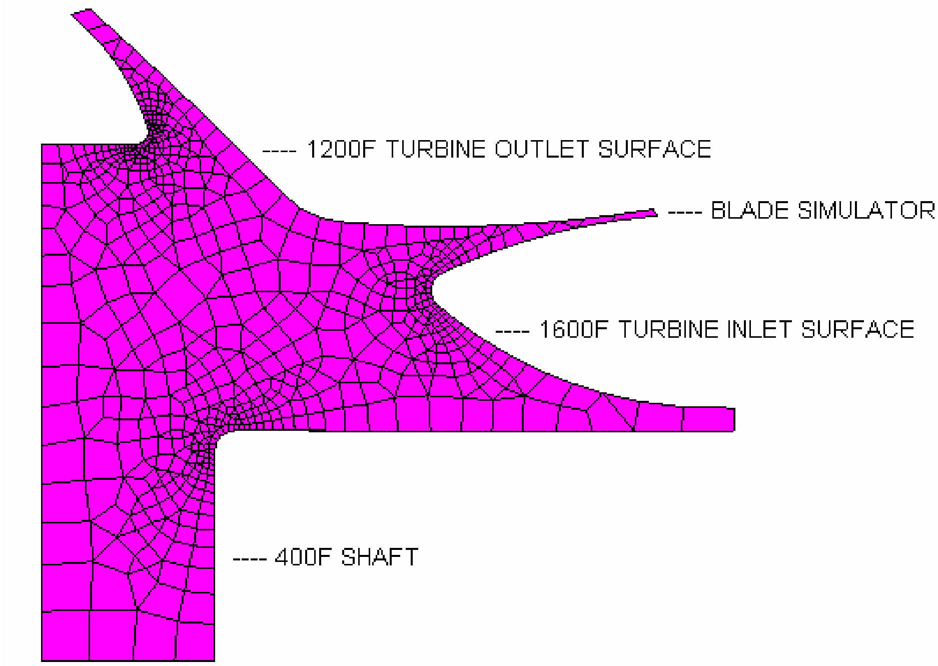


Figure 5.—Finite element mesh of 2–D axisymmetric turbine wheel model. Wheel has a 3 in. (7.62 cm) radius.

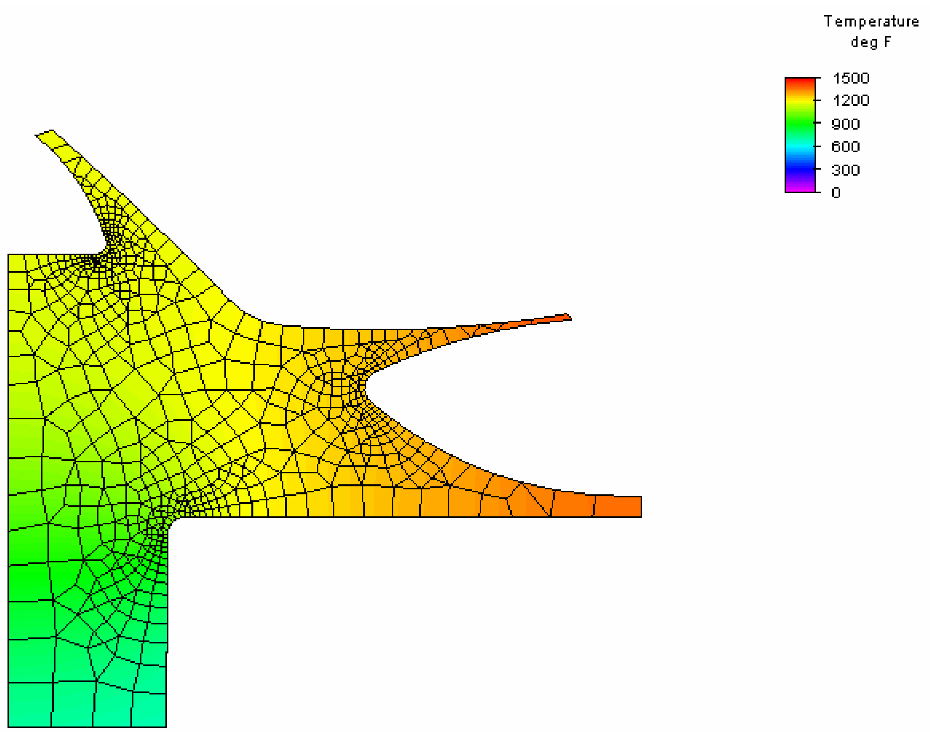


Figure 6.—Temperature distribution in turbine wheel. Maximum wheel temperature is 1405 °F (1036 K).

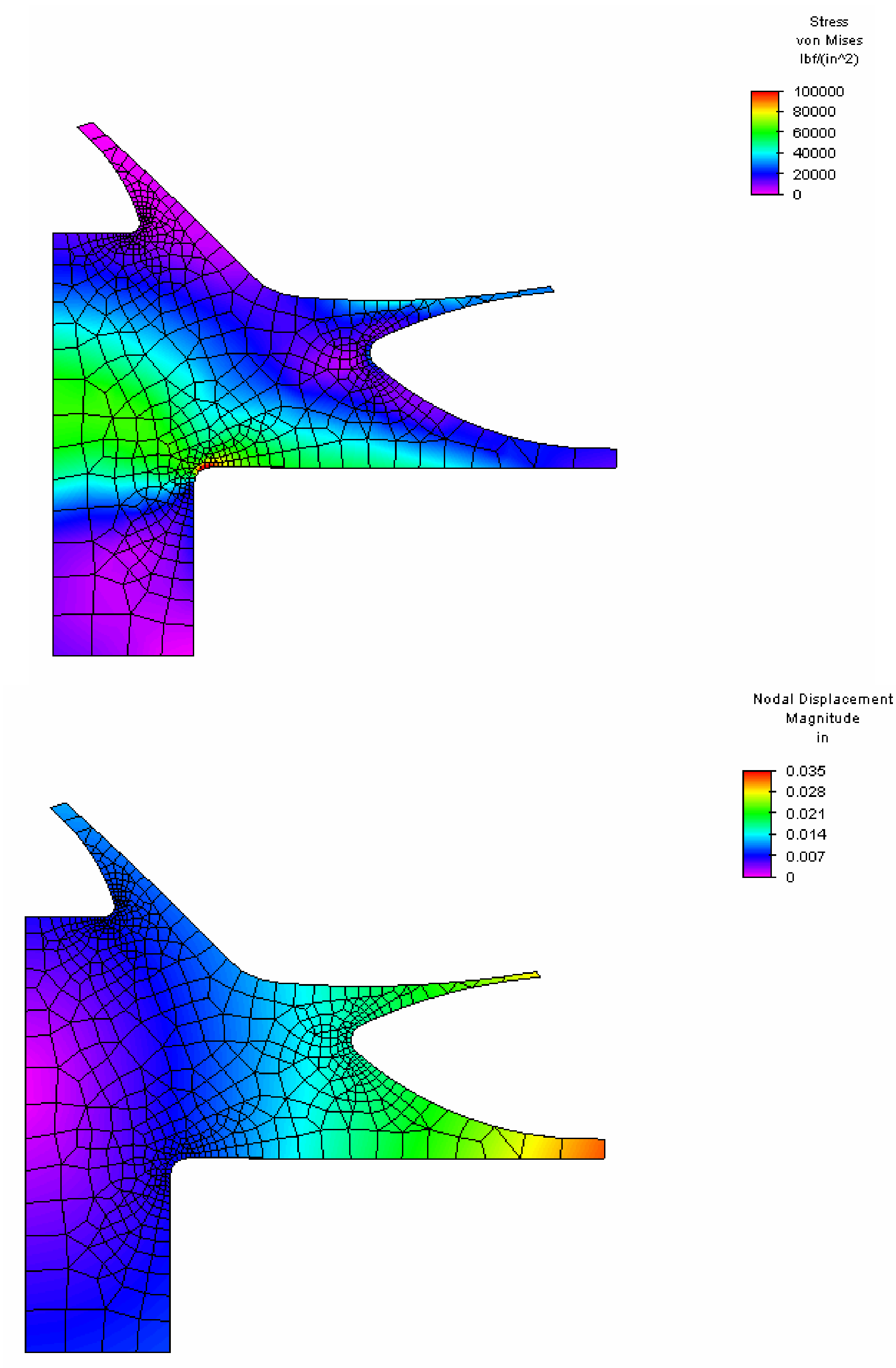
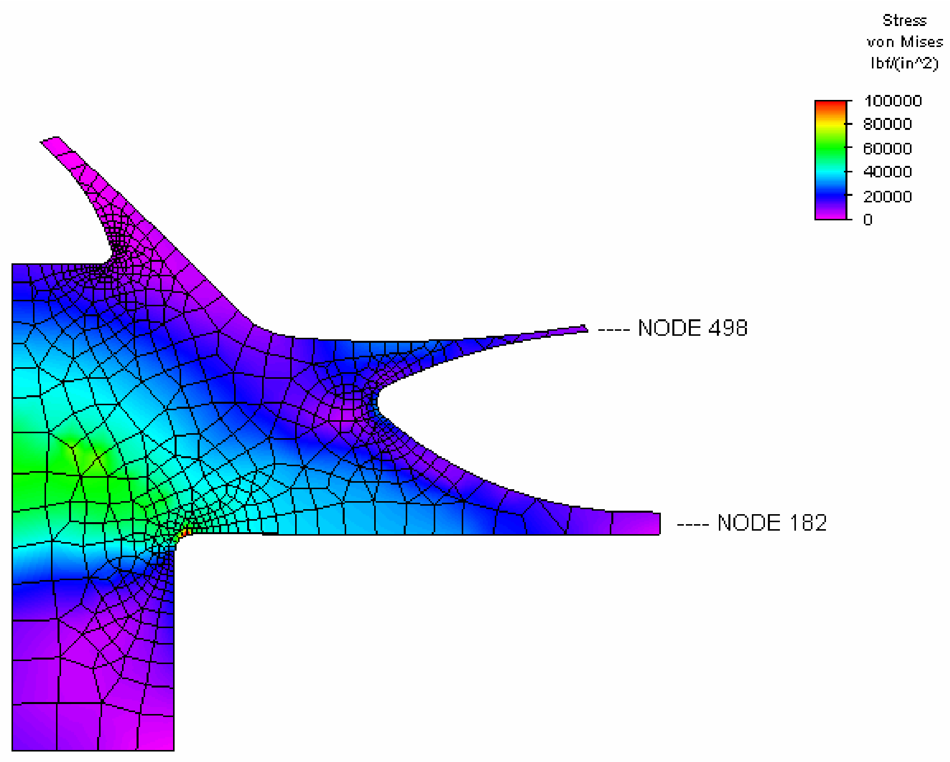


Figure 7.—Wheel stress and growth (displacement) at 45,000 rpm shortly after achieving the operating temperature distribution shown in figure 6.



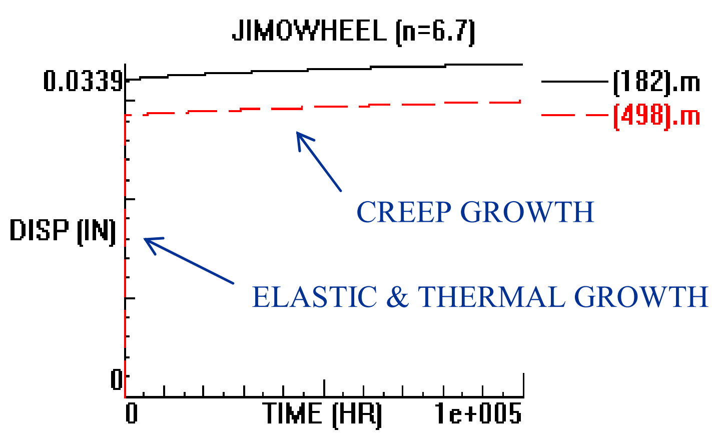


Figure 8.—Wheel stress distribution and radial growth at nodes 182 (wheel) and 498 (blade tip) after 100,000 hours of operation.

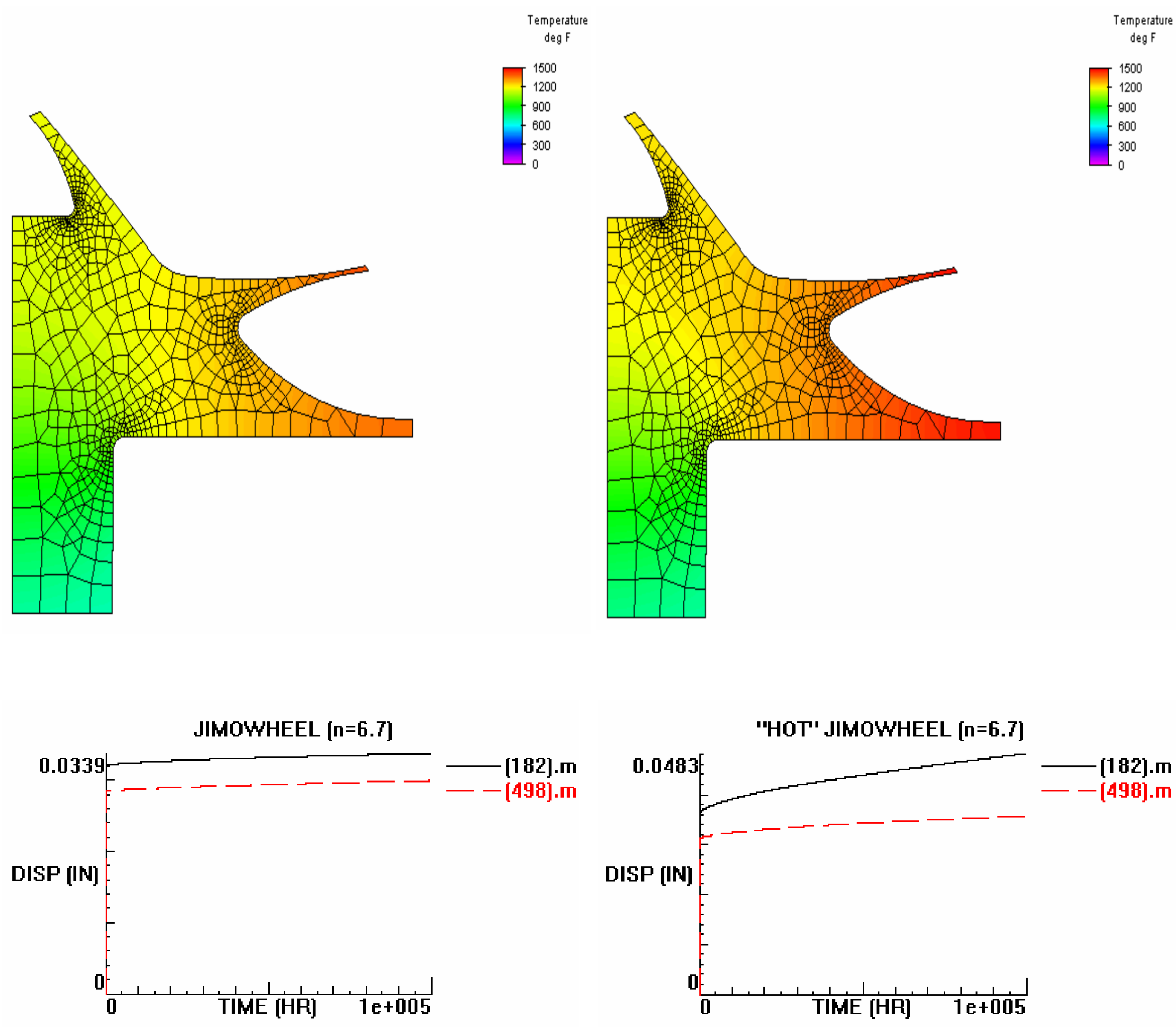


Figure 9.—Comparison of radial growth at nodes 182 (wheel) and 498 (blade tip) after 100,000 hours of operation with different temperature distributions derived from varying heat transfer assumptions.

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13. ABSTRACT ***(Maximum 200 words)***

The designers of the Jupiter Icy Moons Orbiter (JIMO) are investigating the potential of nuclear powered-electric propulsion technology to provide deep space propulsion. In one design scenario a closed-Brayton-cycle power converter is used to convert thermal energy from a nuclear reactor to electrical power for the spacecraft utilizing an inert gas as the working fluid to run a turboalternator as described in L.S. Mason, "A Power Conversion for the Jupiter Icy Moons Orbiter," Journal of Propulsion and Power, vol. 20, no. 5, pp. 902–910. A key component in the turboalternator is the radial flow turbine wheel which may be fabricated from a cast superalloy. This turbine wheel is envisioned to run continuously over the life of the mission, which is anticipated to be about ten years. This scenario places unusual material requirements on the turbine wheel. Unlike the case of terrestrial turbine engines, fatigue, associated with start-up and shut-down of the engine, foreign-object damage, and corrosion issues are insignificant and thus creep issues become dominate. The purpose of this paper is to present estimates for creep growth of a prototypical JIMO turbine wheel over a ten year life. Since an actual design and bill of materials does not exist, the results presented in this paper are based on preliminary concepts which are likely to evolve over time. For this reason, as well as computational efficiency, a simplified 2–D, in lieu of a 3–D, viscoelastic, finite element model of a prototypical turbine wheel will be utilized employing material properties for the cast superalloy MAR-M247. The creep data employed in this analysis are based on preliminary data being generated at NASA Glenn Research Center.

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